



**HAL**  
open science

## Fiber-based source of 200 fs 1.1 $\mu\text{J}$ pulses at 1560 nm for high harmonic generation in solids

M Jedidi, I Tiliouine, L Ferhat, Y Leventoux, F Delahaye, F Amrani, Frédéric Gêrôme, F Benabid, S Février

### ► To cite this version:

M Jedidi, I Tiliouine, L Ferhat, Y Leventoux, F Delahaye, et al.. Fiber-based source of 200 fs 1.1  $\mu\text{J}$  pulses at 1560 nm for high harmonic generation in solids. Optique Normandie, SFO, Jul 2024, Rouen, France. pp.Post02. hal-04643360

**HAL Id: hal-04643360**

**<https://hal.science/hal-04643360>**

Submitted on 10 Jul 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Fiber-based source of 200 fs 1.1 $\mu$ J pulses at 1560 nm for high harmonic generation in solids

M. Jedidi<sup>1</sup>, I. Tiliouine<sup>1</sup>, L. Ferhat<sup>1</sup>, Y. Leventoux<sup>1</sup>, F. Delahaye<sup>2</sup>, F. Amrani<sup>2</sup>,  
F. G r me<sup>2</sup>, F. Benabid<sup>2</sup> and S. F vrier<sup>1</sup>

<sup>1</sup>*Universit  de Limoges, XLIM, UMR CNRS 7252, Limoges, France*

<sup>2</sup>*GPPMM Group, XLIM Institute, CNRS UMR 7252, University of Limoges, Limoges, 87060, France*

*melek.jedidi@unilim.fr*

## ABSTRACT

We propose a fiber-based system providing 1560 nm, 200 fs, 1.1  $\mu$ J pulses at 1 MHz. The pulses from a chirped pulse amplifier based on two amplification stages are first compressed in a bulk compressor and then post-compressed in an Argon-filled hollow-core fiber. The setup can be used for high harmonic generation in solid materials.

## 1. INTRODUCTION

High harmonic generation (HHG) in atomic gases is the basis for producing attosecond pulses [1]. In this extreme nonlinear phenomenon, the high instantaneous surface power density achieved drives the emission of high-order harmonics of the fundamental laser frequency down to the extreme-ultraviolet. In 2011, the demonstration of HHG in large bandgap semiconductor (zinc oxide, ZnO), initiated the field of solid HHG [2]. In their seminal work, Ghimire et al. used long laser wavelength  $\lambda$  in the mid-infrared ( $\lambda = 3.25 \mu\text{m}$ ) because the increased damage threshold of solid materials in the mid-infrared allows for applying electric fields nearly as strong as the critical electric field strength. This contributes to a decrease of the cut-off wavelength, observed at H25 for 2.63  $\mu\text{J}$ , 83 fs pulses. The drive laser pulses were produced in a complicated system by difference-frequency generation between a femtosecond Ti:sapphire laser and a picosecond Nd:YLF laser. Recently, we demonstrated that solid HHG can actually be obtained from an oscillator-like fiber laser at 2.1  $\mu\text{m}$  by tailoring the geometry of the solid material [3]. We also demonstrated solid HHG up to the 7th harmonic (limited by our detection system) from a fiber-based laser source delivering 1.7  $\mu\text{m}$ , 40 nJ, 70 fs pulses [4]. Our recent studies showed that HHG can actually be expected from near-infrared wavelengths, too, which are much easier to achieve than mid-infrared wavelengths. Nevertheless, our experiments were limited to relatively low-order harmonics (H7, H9) due to a lack of energy. In order to increase the HHG cut-off frequency, pulses with sub-200 fs durations but microjoule-level energy are needed. However, microjoule-class femtosecond laser sources at 1560 nm are scarce. Ilday et al. succeeded in developing a laser source delivering 2  $\mu\text{J}$  pulses with 400 fs [5]. Krylov et al. achieved 10  $\mu\text{J}$  energy pulses with 740 fs duration [6]. These impressive results are not compatible with HHG due to too long a pulse duration. The goal of the present work is to produce microjoule-class sub-200 fs pulses in the telecom band from a fiber-based system, in order to reach extreme ultraviolet by HHG in a compact design. Such performances are obtained from an in-house built chirped pulse amplifier followed by nonlinear post-compression in custom-made Ar-filled hollow-core fiber.

## 2. EXPERIMENTAL RESULTS

The experimental setup for production of microjoule-class femtosecond pulses at 1560 nm is depicted in Fig.1.

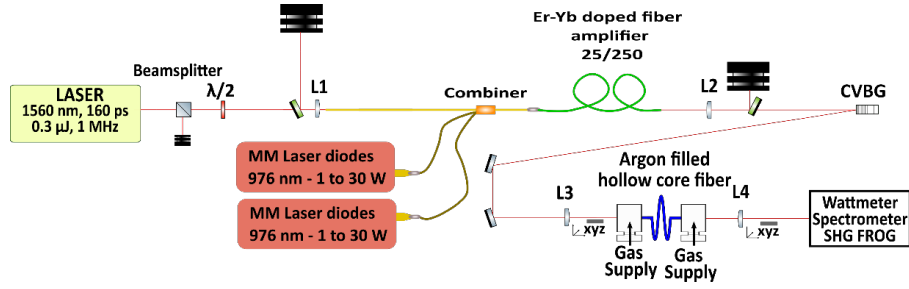


Figure 1 : Experimental setup of the laser system.

The system starts from a chirped pulse amplifier (CPA) delivering 1560 nm, 160 ps, 0.3  $\mu\text{J}$  pulses at a repetition rate of 1 MHz. The pulse train is launched into a second amplifier stage based on an Erbium-Ytterbium co-doped fiber (EYDF) pumped by two pigtailed multimode diodes providing up to 60 W at 976 nm. The active fiber was chosen after several tests on various double-clad Erbium-doped fibers. By comparing the various experimental results, we found that the best fiber in terms of beam quality and gain was the EYDF 25/250 from Exail with a numerical aperture of 0.085. The optimal fiber length, which led to the highest average power, was found to be 2 m. We obtained up to 3.2  $\mu\text{J}$  at 1560 nm as shown by the black curve in Fig.1a. The 160 ps pulses were then compressed in a chirped volume Bragg grating (CVBG) matched to the stretcher of the CPA. The pulse was characterized by second-harmonic frequency-resolved optical gating (SH-FROG). Fig.2b shows the FROG trace obtained at the highest power. The pulse duration was measured to 1.7 ps. The energy after the compressor was decreased to 2.3  $\mu\text{J}$  (Fig.2a red plot). It is worth noting that the amplifier is not limited to 3.2 W. The output power was indeed increased up to 8 W at the cost of increased nonlinearities in the amplifier, which decreased the compression efficiency. The output power was therefore kept to 3.2 W for the rest of the experiments.

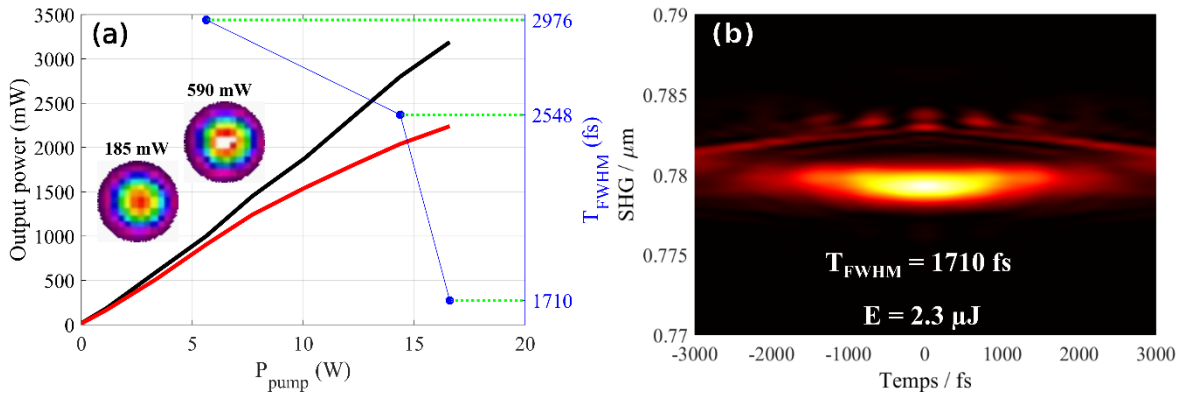


Figure 2 : (a) Output power before (black) and after (red) the compressor. Insets show near-field intensity distribution for two output powers. (b) FROG trace recorded for 2300 mW after the compressor.

Then, the 1.7 ps, 2.3  $\mu\text{J}$  pulses were launched into an Argon-filled hybrid Kagome-tubular hollow-core photonic crystal fiber (HC-PCF) [7] with a core diameter of 32  $\mu\text{m}$  for nonlinear post-compression. The fiber exhibits remarkable characteristics, including losses at the pump wavelength of 1560 nm, hovering around 30 dB/km. When the fiber is filled with nonlinear gas (e.g. Argon), and provided the pulse peak power is sufficiently high, the self-phase modulation (SPM) broadens the pulse spectrum. The interplay between the anomalous dispersion of the fiber mode and SPM then leads to temporal compression. In our experiments, we introduced 8 bars of argon into the HC-PCF connected to two gas cells (Glophotronics), leading to a nonlinear index  $n_2 = 6.4 \times 10^{-23} \text{ m}^2/\text{W}$  and a dispersion coefficient  $D = 5.8 \text{ ps}/(\text{nm}\cdot\text{km})$ . The spectrum of the launched pulses (1.7 ps, 2.3  $\mu\text{J}$ , 1.35 MW peak power) was significantly broadened as shown in Fig.3a. The FROG trace was recorded after the Ar-filled HC-PCF for two average power, and plotted in Fig. 3b. The pulses were compressed down to 200 fs, i.e. by a factor of 8, in the HC-PCF. The overall launching efficiency in the nonlinear post-compression stage

(including two gas cells and 3 m of hollow core fiber) was 50%, leading to output pulse energy of 1.1  $\mu\text{J}$ , which corresponds to 4.25 MW peak power.

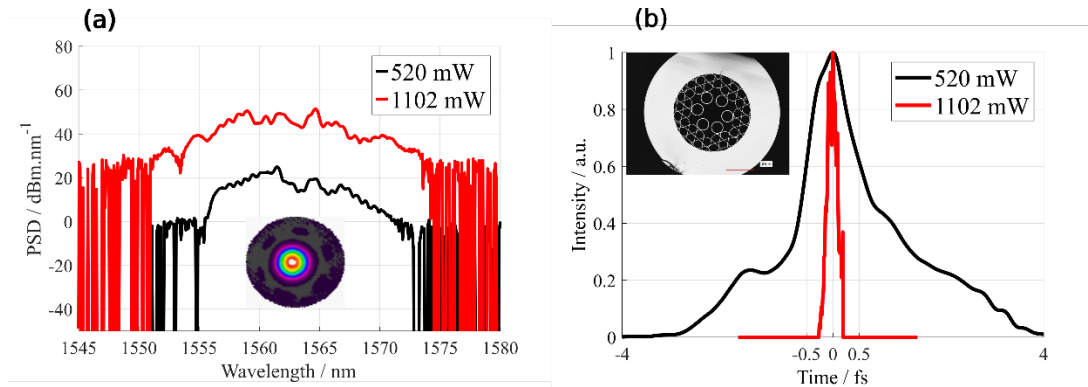


Figure 3: Spectral (a) and temporal (b) profiles of the pulse at the output of the HC-PCF recorded for 520 mW (black) and 1100 mW (red). Insets show the near-field intensity distribution (a) and fiber cross-section (b).

### 3. CONCLUSION

In summary, we have reported on a fiber-based system providing 1560 nm, 200 fs, 1.1  $\mu\text{J}$  pulses at 1 MHz. The pulses from a chirped pulse amplifier based on two amplification stages were first compressed in a bulk compressor and then post-compressed in an Argon-filled hollow-core fiber. The system has strong potential as a driver source for high harmonic generation in the extreme ultraviolet. Additional results on the high-harmonic generation in solid targets will be presented at the conference.

### FINANCEMENT

H2020 Future and Emerging Technologies (PETACom 829153) ; Agence Nationale de la Recherche (ANR-20-CE42-0003 FLEX-UV) ; Conseil Régional de Nouvelle-Aquitaine (Femto-VO2, MIR-X).

### REFERENCES

- [1] F. Krausz and M. Ivanov, "Attosecond physics," *Rev. Mod. Phys.* 81, 163 (2009)
- [2] S. Ghimire, A. D. DiChiara, E. Sistrunk, P. Agostini, L. F. Di Mauro, and D. A. Reis, "Observation of high-order harmonic generation in a bulk crystal," *Nat. Phys.* 7, 138 (2011).
- [3] D. Franz, S. Kaassamani, D. Gauthier, R. Nicolas, M. Kholodtsova, L. Douillard, J.-T. Gomes, L. Lavoute, D. Gaponov, N. Ducros, S. Février, J. Biegert, L. Shi, M. Kovacev, W. Boutu, and H. Merdji, "All semiconductor enhanced high-harmonic generation from a single nanostructured cone," *Sci. Rep.* 9, 5663 (2019)
- [4] M. Jedidi, Y. Leventoux, L. Ferhat, C. Jimenez, I. Tilouine, G. Granger, J.-C. Orlianges, A. Crunteanu, L. Lavoute, D. Gaponov, J. Boulet, M. Froidevaux, W. Boutu, H. Merdji, V. Couderc and S. Février, "High-Energy Solitonic Source of High Harmonics". *Advanced Solid-State Lasers* (2022). Technical Digest Series Optica Publishing Group, paper ATu4A.8 (2022).
- [5] S. Pavlova, H. Rezaei, I. Pavlov, H. Kalaycıoğlu, F. Ö. Ilday, "Generation of 2- $\mu\text{J}$  410-fs pulses from a single-mode chirped-pulse fiber laser operating at 1550 nm". *Applied Physics B*, 124(10), 201 (2018).
- [6] A. Krylov, A. Senatorov, A. Gladyshev, Y. Yatsenko, A. Kosolapov, A. Kolyadin, M. Khudyakov, M. Likhachev, and I. Bufetov, "10- $\mu\text{J}$ -level femtosecond pulse generation in the erbium CPA fiber source with microstructured hollow-core fiber assisted delivery and nonlinear frequency conversion," *Appl. Opt.* 62, 5745-5754 (2023).
- [7] F. Amrani, J. Osorio, F. Delahaye, F. Giovanardi, L. Vincetti, B. Debord, F. Gérôme, F. Benabid "Low-loss single-mode hybrid-lattice hollow-core photonic crystal fiber". *Light: Science & Applications*, 10(1), 7 (2021).